OBSERVATIONS BEARING ON THE THEORY OF STELLAR CONVECTION II

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SUMMARY

It is shown that the best way to get information about efficiency of convective energy transport in the hydrogen convection zones in stars other than the sun is presently contained in continuous energy distributions of A and F stars. Scans show that convective energy transport must be much more efficient than thought hitherto. The scans indicate that rapid rotation enhances convective energy transport.

Figure 1 lists all the observations, we could think of, which are influenced by the outer convection zone and which can therefore give us information for our convection theory.

I. STELLAR STRUCTURE AND EVOLUTION

Already Hoyle and Schwarzschild (1955) pointed out that with increasing efficiency of convection the radius of a star shrinks.

If we describe the efficiency of convection by the one parameter ℓ, the characteristic length or the mixing length of the convective flow, and if we further assume that the ratio $\ell/H = \alpha$ is depth independent, where H is the pressure scale height - an assumption that may not be valid, see for instance Böhm (1958), Schwarzschild (1974) - then this one parameter α can in principle be determined from the observed radius of the star. Unfortunately, the radius depends also on the initial abundances Z, Y and CNO (Iben 1963) as well as on the age of the star. From Iben's study we see that for given T_e a $\Delta \log L \sim 0.3$ is obtained for $\Delta \log \alpha \sim 0.5$, but one also finds $\Delta \log L \sim 0.3$ for a change in abundances Y and Z by a factor of 2. A similar change in log L is obtained if opacities are computed with different approximations. Different authors therefore obtain different values of α from the radii of the sun and the stars, ranging from $\alpha = 0.4$ to $\alpha = 2$. From the position of the main sequence we can therefore presently only conclude that $\log \alpha = 0 \pm 0.5$.

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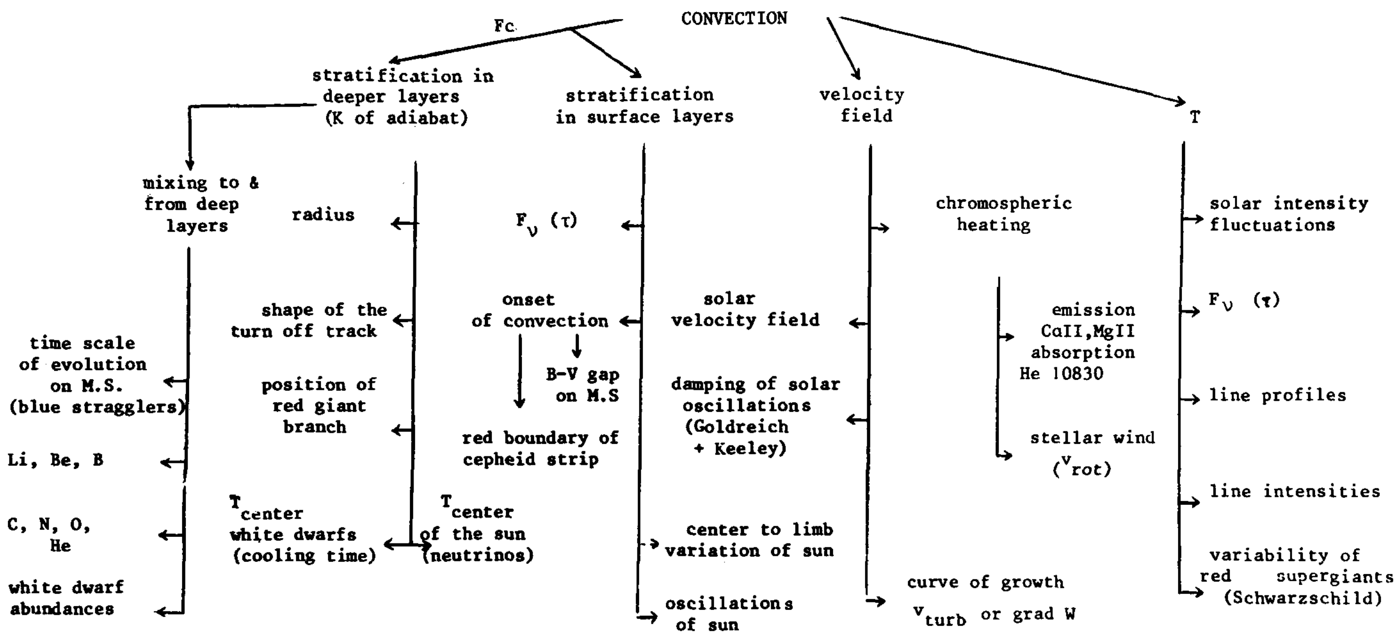

FIGURE 1

Ways in which the effects of the outer convection zones appear in astronomical observations and which therefore can give us information about convection theory.

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The same difficulties apply to studies of the evolutionary tracks which again depend on Z, Y and α and also C, N, O abundances. In fact one would like to know α in order to find the other parameters.

An additional difficulty is encountered when studying H.R. diagrams: In order to compare theoretical and observed tracks we have to relate the theoretical parameters T_e and g to the observed ones: color and m_v or M_v. The relation between the color and T_e, g depends not only on Z, and the CNO abundances, but also on the influence of convection on the observed energy distribution, i.e. the changes of the T (τ) relation in the surface layers. This could possibly be important on the whole evolutionary tracks for stars of spectral types F and later.

There are several indications that the colors are indeed influenced by surface convection :

(a) Theoretical color computations for giants in radiative equilibrium giving U - B as a function of Z for a given value of B - V show a maximum of U - B for $Z \sim 0.3 \cdot Z_\odot$ (Böhm-Vitense and Szkody 1974). This maximum is not well seen in the observations (Wallerstein et al. 1966).

(b) For intermediate Z values we find a discrepancy between the observed and computed M_4 = (B - V) - (V - r) index (Mannery et al. 1968) for giants in radiative equilibrium (Böhm-Vitense and Szkody 1974).

(c) Canterna (1976) finds similar problems for his metallicity index C - M.

All these discrepancies show that for a given energy distribution in the red there is less energy observed in the blue and violet region than predicted by the radiative equilibrium models. Scaled solar Bilderberg models, i.e. models with a decreased temperature gradient in the deeper layers, would ease the problem. It might be emphasized however, that the discrepancies only exist for giants with $0.1\ Z_\odot \leq Z < Z_\odot$, not for very metal poor stars. It could, therefore, also be related to an error in the line blanketing computation, for instance a wrong value for the microturbulence.

While the decreased ultraviolet flux is in itself an interesting problem and might well tell us something about convective overshoot in stars with different Z, it also tells us that we have to study and understand this convective overshoot before we can deduce the "observed" evolutionary tracks in the L, Te diagram and proceed to determine Z, Y, C, N, O, the age t, and finally α .

We then conclude that the stellar evolution computations require a knowledge of α rather than provide one.

II. SURFACE PHENOMENA

A. DIRECT MEASUREMENT OF VELOCITY FIELDS

The most direct observations of convection are the velocity fields which for stars can only be observed by broadened line profiles. If the velocity field changes over one mean free path of a photon it will lead to a broadening of the line absorption coefficient thereby increasing the line width and the equivalent width. If the velocity changes only over much larger scales it will lead to a broadening of the intensity profile only and not change the equivalent widths of the lines. According to the influence on the equivalent width we describe the two effects as micro or macro-turbulence (or possibly rotation). However, we have to keep in mind that an increase in the equivalent width could also be due to other effects than small scale velocity fields. Also there is no reason why we should have only small scale or large scale turbulence, in fact we expect a continuous turbulence spectrum of all scales. (For isotropic turbulence see the discussions by H. and U. Frisch 1975, by G. Traving 1975 and by E. Sedlmayr 1975). Therefore, we have to be careful with the interpretation of the socalled microturbulence. If we believe that the microturbulence as determined from the equivalent widths by means of curve of growth analysis really is a measure for the small scale velocity field, which could be either due to turbulence or to laminar velocity gradients, then we find the picture first compiled by Wright 1955, see Figure 2.

Generally the microturbulence increases for decreasing densities in stellar atmospheres as is expected for convective velocities: Since the convective flux $F_c \propto \rho \cdot V^3$, ρ = density, V = convective velocity, we expect for a given $F_c \sim F$, where F is the total energy flux, that $V \propto \rho^{-1/3}$. We do however not observe the decrease of the microturbulence for hot stars for which $F_c \ll F$ is expected.

A compilation of more recent data especially for giants has been given and discussed by Reimers (1976).

For supergiants Rosendhal (1970) and van Paradijs (1973) have more recent studies, qualitatively confirming the results shown by Wright (1955).

For main sequence stars Baschek and Reimers (1969) did a detailed investigation especially in order to study possible differences between A_m and normal A stars. Chaffee (1970) extended the study to cooler stars. Andersen (1973) repeated the determination with the new FeI oscillator strengths (Garz and Kock 1969). The result is shown in Figure 3. An increase in V_{turb} is found when going from late F to early F stars in quantitative agreement with convective velocities obtained for $\alpha \simeq 1$. However, for earlier stars the expected decrease in velocities is not found. For later stars an increase in V_{turb} is suggested - though not observed for the sun - also in contradiction to expectations from convection theory.

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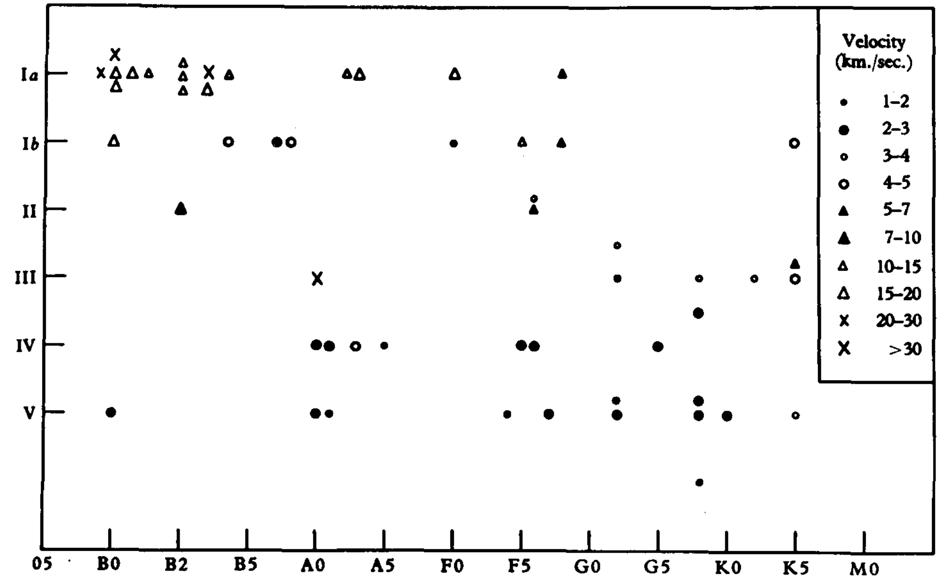

FIGURE 2:

Microturbulent velocities for stars of different spectral types and luminosity classes as given by Wright (1955).

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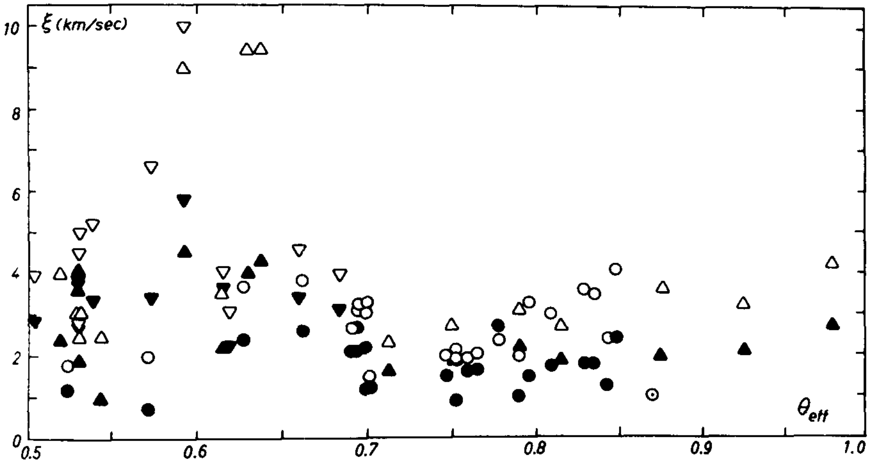

FIGURE 3:

Microturbulent velocities for main sequence stars of different effective temperatures according to Andersen (1973). The open symbols refer to previous investigations by Baschek and Reimers (1969) and Chaffee (1970) using old oscillator strengths, the filled symbols to Anderson's determination with the Garz and Kock (1969) oscillator strengths. ∇, ▼ refer to A_m stars.

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Another puzzle is provided by the measurements of Allen and Greenstein (1960) and Wallerstein (1962) showing that in Pop. II dwarfs $V_{turb} \leq 0$, a result which is certainly not expected from convection theory, but these studies will have to be repeated with new FeI oscillator strengths in order to be sure. Reimers (1976) attributes the increase of V_{turb} for late type stars to possible measuring errors. Baschek and Reimers (1969) suggest that for the A stars the high V_{turb} is caused by a large number of pulsation modes similar to the ones studied recently by Lucy (1976) for α Cyg.

In short, measured values of V_{turb} sometimes do and sometimes do not agree even qualitatively with exceptations from convection theory, indicating either that our expectations are sometimes quite wrong, or more likely, that the measured microturbulence has quite often nothing to do with convective velocities. How then do we know when they do and when they do not ?

Even more difficult is the judgement of the observed depth dependence of the microturbulence (Huang and Struve 1952, Rosendahl 1970). In general there does not seem to be any observed contradiction to the assumption that for other stars the depth dependence of V_{turb} is similar to the one observed for the sun.

B. INDIRECT MEASUREMENTS OF VELOCITY FIELDS BY MEANS OF ATMOSPHERES AND CORONAE

(a) Chromospheric emission :

It is general belief that for the formation of classical solar type chromospheres a velocity field is a necessary condition. We do not know whether it is also a sufficient condition. The different strengths and the age dependence of the CaII K_2 emissions for otherwise similar stars show the importance of a second parameter, probably the magnetic field. The absence of chromospheric emission may therefore not be proof of the absence of a velocity field, only, if for a given spectral type we never find chromospheric emission, I would believe this to indicate the absence of efficient convection.

Chromospheres in cooler stars are seen by means of CaII K_2 and MgII h and k emission or by the 10830 line of HeI in absorption. O.C. Wilson (1976) has made extensive studies of the CaII K_2 emission in G and K stars. His results are shown in Figure 4. In the same graph I have also plotted the bluest stars that have been observed to show MgII emission and 10830 HeI absorption according to Zirin (1975). There appears to be a line in the HR diagram on the blue side of which the chromospheric activity seems to stop. In the low luminosity part is not quite clear to me whether the CaII K_2 emission stops for somewhat more red stars than the MgII emission. If so, it could be an effect of the larger abundance and ionization energy of MgII. If they stop at the same time it should indicate a cause different from ionization.

In the same graph I have also plotted the reddest Pop. I Cepheids according to Sandage and Tammann (1971).

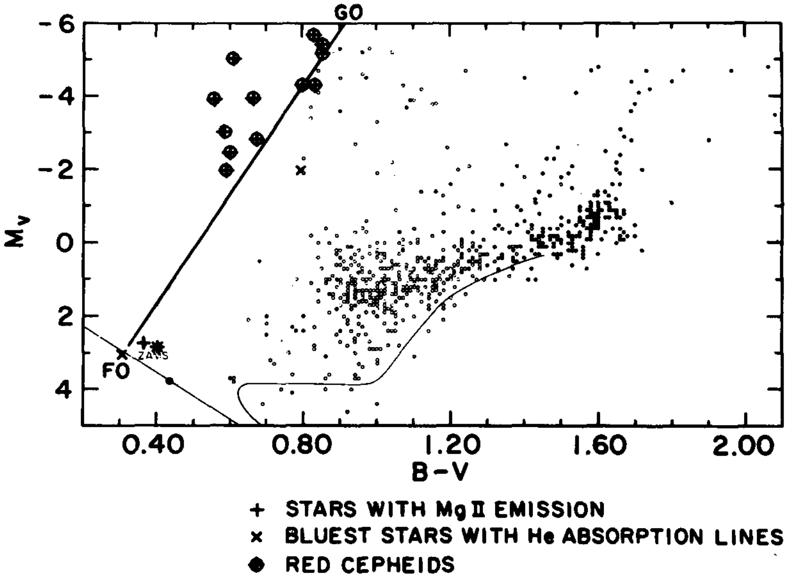

FIGURE 4:

The color magnitude diagram for G and K stars with CaII K_2 emission (oo●●) taken from Wilson (1976). We have added an additional point for Procyon (FOIV). We have also added ++ for the bluest stars observed to have MgII h and k emission and xx for the bluest stars showing He absorption lines (Zirin 1975). Also shown are the positions for Cepheids close to the red boundary of the instability strip. The straight line roughly marks the boundary for stars with or without observed signs of solar type chromospheres.

For the higher luminosities the red boundary of the instability strip appears to agree roughly with the boundary line for CaII and MgII emission. There is of course CaII K_2 emission observed for some Cepheids and also for α Cyg but this is supposedly due to shockwaves created by pulsation. The agreement of these two boundary lines is not surprising since we see no other reason for the breakdown of the pulsational instability but the onset of efficient convection which reduces F_{rad}, thereby reducing the driving force.

Since the theoretical line for the onset of efficient convective energy transport depends on α we can check which α should be chosen to make the theoretical and observed boundary lines agree. Assuming that α is the same for all stars in this region - an assumption which has been criticized by Schwarzschild (1974) - we found agreement for $\alpha \simeq 0.5$, 2, 3 or 5. This can be seen from Figure 5 (Böhm-Vitense and Nelson 1976). (If α should not be same for all stars, then $\ell \propto R^2$ appears to be also a possibility except for Ia supergiants.)

As already noted earlier, the extension of the instability strip boundary reaches the main sequence at about F0 or B - V ∿ 0.3. So F stars would be expected to have efficient convection, while A stars would not, but they appear in the extension of the instability strip, as mentioned earlier.

(b) Stellar rotation:

It has been suggested that stellar rotation will be braked by means of the stellar wind and the magnetic field. (See for instance Kippenhahn 1972; further references are given there.) Since stellar winds for later type stars are due to the presence of coronae which are linked to stellar convection zones, the decrease of the rotational velocities for the F stars may also mark the onset of efficient convection. In Figure 6 (Böhm-Vitense and Canterna 1974) we show the dependence of the rotational velocities on B - V for main sequence stars for different clusters. For field stars there is a drop in $v_r \sin i$ for B - V ∿ .25; a second drop seems to appear for B - V ∿ 0.4. For some of the clusters the drop at B - V = 0.40 is the more pronounced one. Apparantly the final drop in $v_r \sin i$ does not occur where we expect convection to set in but only for cooler stars. It seems to occur at temperatures where the hydrogen and helium convection zones merge.

C. TEMPERATURE INHOMOGENEITIES

Convective temperature inhomogeneities are expected to be largest for F stars. We might look for evidence in the integrated light.

In Figure 7 we compare continuum energy distribution of stars whose surface is assumed to be half covered with an atmosphere with $T_e \sim 6800°$ and half with $T_e = 8340°$. The average would be 7500°. The resulting energy distribution would appear as that of an atmosphere with $T_e \simeq 7750°$. The inhomogeneous atmosphere, therefore, would re-

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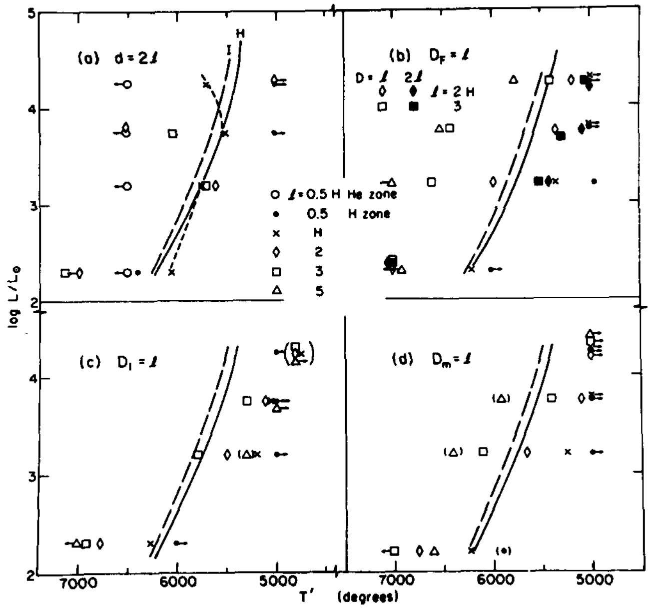

FIGURE 5:

Taken from Böhm-Vitense and Nelson (1976) this figure shows a comparison of theoretical and observed (— — — or ————) boundary lines for efficient convection in the luminosity T_e diagram (T_e = T'-400 ± 150°). Different values for the ratio of the mixing length ℓ to the pressure scale height H were assumed. Symbols are given in the graph.

To obtain the points in Figure a we required that $\ell \leq \frac{1}{2}$ D for a consistent theory, where D is the thickness of the unstable layer. The theoretical (----) and observed boundary lines agree roughly for ℓ = H.

For the points in Figure b we assumed that $\ell \leq D_F$, where D_F is the extent of the zone where $F_c \geq 10^{-2} \cdot F$, where F is the total flux and F_c is the convective flux. No agreement between observed and theoretical boundary line can be found for any value of ℓ/H.

In Figure c we required $\ell = D_1$ at the boundary, where D_1 is the extent of layer for which $\nabla - \nabla' > 0.1$, with the usual notation. No agreement between theoretical and observed boundary can be found.

In Figure d we required $\ell = D_m$ at the boundary, where D_m is the extent of the layer for which $\nabla - \nabla' = 0.1\ (\nabla - \nabla')_{max}$, where $(\nabla - \nabla')_{max}$ is the maximum value of $\nabla - \nabla'$ in the convection zone under consideration. No agreement can be found between observed and theoretical boundary lines.

For details of the derivation see Böhm-Vitense and Nelson (1976).

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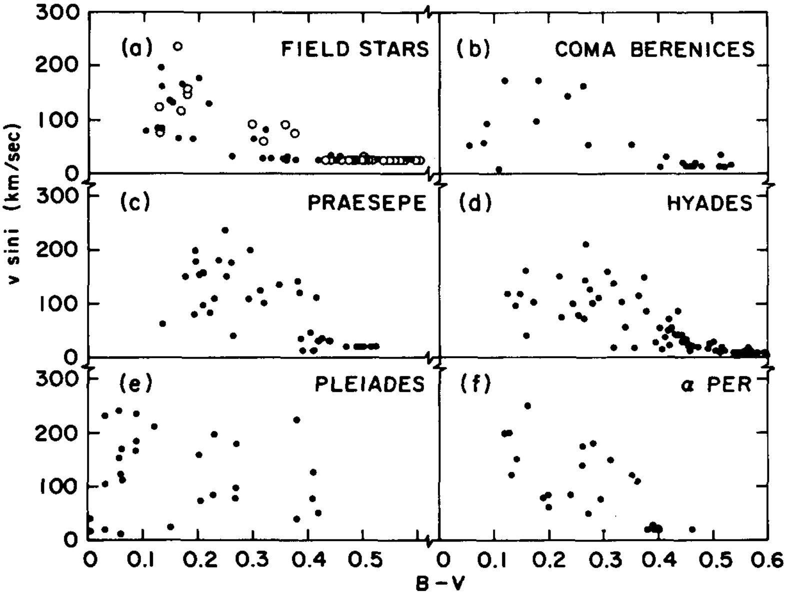

FIGURE 6:

The rotational velocity for field stars and for stars in different clusters. Two discontinuities in the velocity distribution of field stars are suggested, one at B − V ∿ 0.25 and the other at B − V ≃ 0.40. For the clusters the decrease of vsin i at B − V ∿ 0.40 is more pronounced. The figure is based on measurements by (a): Abt and Hunter 1962 and Slettlebak 1955; (b) and (d): Kraft 1965; (c): Dickens et al. 1968; (e): Andersen et al. 1966; (f): Kraft 1967.

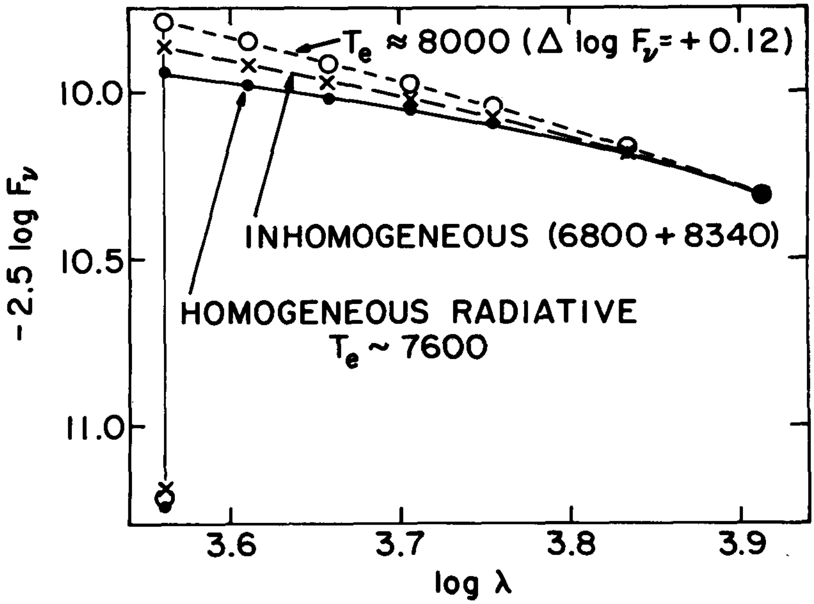

FIGURE 7:

The continuum energy distribution of a star whose surface is half covered with an atmosphere with $T_e = 6800^o$ and half with $T_e = 8340^o$ is compared with the continuum energy distribution of stars with $T_e = 8000^o$ (shifted by $\Delta \log F_\nu = 0.12$) and $T_e = 7600^o$. The energy distribution of the inhomogeneous star is indistinguishable from that of a homogeneous star with $T_e \sim 7750^o$.

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semble one with a temperature about 250° higher than its actual T_e.

In Figure 8 (from Böhm-Vitense 1972) we compare line profiles of a homogeneous star and an inhomogeneous one with $\Delta T = \pm 1000°$. The T_e and the corresponding fractions of the surface area on the inhomogeneous star were chosen in such a way that in $H\gamma$ the lines agree for both the homogeneous and the inhomogeneous stars. The B − V colors then turn out to agree also. One finds that, because of the larger contribution from the hot component, the spectral lines for the inhomogeneous star are generally weaker by $\sim$ 10% than those for the homogeneous one. The effect is especially strong for the Ca lines, which are reduced by about 30%. One is reminded of the A_m stars occurring in this temperature range which show weak Ca lines, however for the A_m stars the other metallic lines appear generally stronger.

D. THE INFLUENCE OF CONVECTIVE ENERGY TRANSPORT ON THE CONTINUOUS ENERGY DISTRIBUTION

The major influence of convection on the stellar structure is due to the convective energy transport which reduces the temperature gradient. If this happens in visible layers then we might be able to see changes in the continuum flux distribution. F stars are especially promising since the instability sets in rather high regions of the atmosphere and we have a pronounced minimum in the continuous absorption coefficient κ_c longward of λ = 3647 Å, where we can see down into the atmosphere to $\bar{\tau} \simeq 2$.

In Figure 9 I have plotted temperature stratifications for various depth dependences of the radiative flux $F_r = F - F_c$. Also shown are the corresponding energy distributions in the visual region for stars with $T_e \sim 7900°$.

The curve shifted upwards (separate scale) shows the depth dependence of the radiative flux as computed with the mixing length theory of convection.

The model with the steepest decrease in F_r is a scaled solar, the socalled Bilderberg model. In an earlier study we had found (Böhm-Vitense 1970) that the UBV colors of main sequence F stars could not be obtained for radiative equilibrium models but that scaled Bilderberg models would do fine. The other models were computed in order to see whether we could reproduce the observed energy distributions with less extreme reductions of the radiative flux. Little change from radiative equilibrium F_ν is obtained for these models.

It is interesting to note the very sensitive dependence of the surface temperatures on the depth dependence of the convective flux. A low surface temperature as obtained for one of the models should be apparent in the line spectrum which should possibly look generally like that of a metallic line star.

From mixing length theory we expect a rather abrupt onset of convection for $T_e \sim 8000°$. When using scaled Bilderberg models for convective stars we find a color change of $\Delta(B - V) = 0.07$ (Böhm-Vitense 1971). A similar value was also obtained by Matsushima and Travis (1973) with their nonlocal theory of convection if they use

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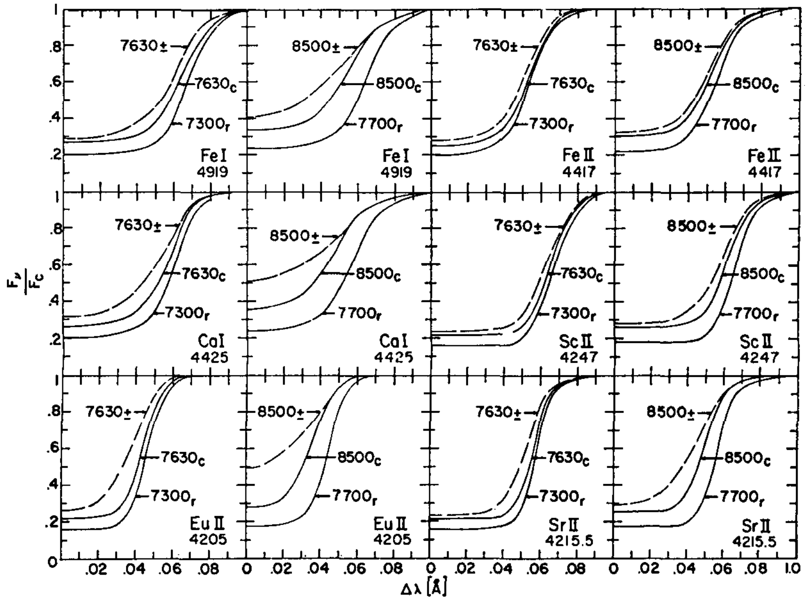

FIGURE 8:

The line profiles of convective stars with $\Delta T_e = \pm 1000°$ are compared with those of a homogeneous (i.e. $\Delta T_e = 0$) convective star and a star in radiative equilibrium. The inhomogenous star shows generally somewhat weaker lines especially of Calcium. The figure was taken from Böhm-Vitense 1970.

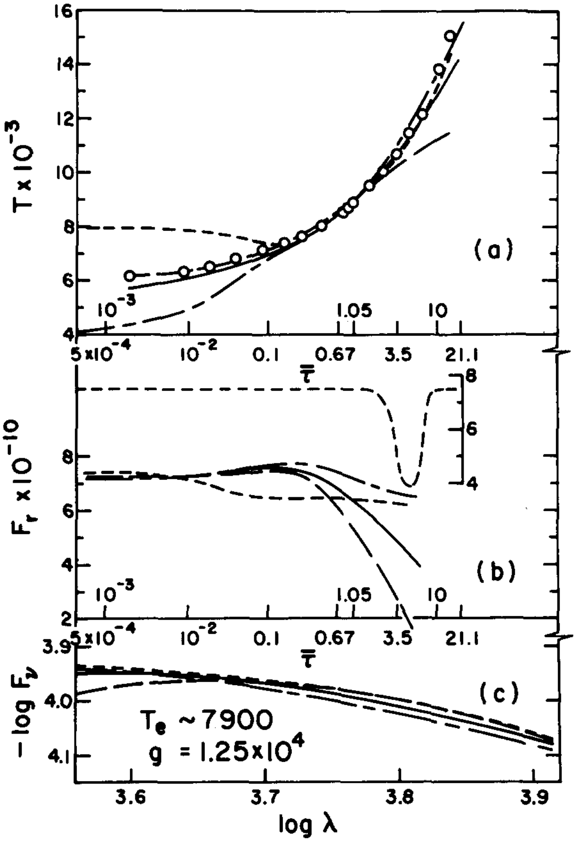

FIGURE 9:

In part (a) we give the temperature stratifications for several models, in part (b) the corresponding depth dependences of the radiative flux and in part (c) the corresponding continuum energy distributions. The ooo in part (a) refer to the radiative equilibrium model for the stable layer and mixing length model for the convective layers. The corresponding depth dependence of the radiative flux is shown by the displaced curve (b) (with sparate scale). The long dashes refer to the scaled Bilderberg model. The other curves refer to trial models that were computed in order to see whether we could also obtain a reduction in the energy emitted just longward of the Balmerjump with a smaller decrease of the radiative flux in layers $\bar{\tau} \gtrsim 1$. This does not seem to be possible.

$\alpha \simeq 1$ (which however,leads to difficulties with the observed solar center to limb variation). This abrupt color change should be observed as a gap in the observed B - V. The presence of a gap at $0.2 < B - V < 0.3$ for field stars was noticed by Mendoza (1956). He also noticed that this gap is not present for Pleiades stars. Figure 10 shows that this gap is indicated more or less pronounced in different clusters (Böhm-Vitense and Canterna 1974), though its position changes slightly for different clusters. We suspect that rotation my have influence on the onset of convection. If this interpretation of the gap is correct, then field stars with $B - V \leq 0.22$ should be in radiative equilibrium, those with $B - V > 0.29$ should be influenced by strong convection, leading to the color change.

Figure 11 shows the result of observations for field stars by Oke (1964), for Hyades stars by Oke and Conti (1965), and by Baschek and Oke (1965) for A_m stars.

In the same Figure we compare these scans - corrected for the change of absolute calibration (Oke and Schild 1970 and Hayes 1975) and for line absorption - with continuum energy distributions for radiative equilibrium models and for scaled Bilderberg models.

The right hand side of Figure 11 shows the result for the Hyades stars. Except for the small deviations around 4000 Å the scans show good agreement with radiative equilibrium models (solid lines) for $B - V < 0.2$ and agreement with the scaled Bilderberg models (dashed curves)for $B - V > 0.3$ as we expected from the study of the colors.

The left hand side shows the results for the field stars, which display the gap very clearly at $B - V = 0.22$. Unexpectedly we see the influence of convection already for β Ari with $B - V \simeq 0.14$.

Figure 12 shows the results for A_m stars. The cooler ones clearly fit convective models and not radiative ones.

We have made additional scanner observations of main sequence Hyades stars with different rotational velocities (Böhm-Vitense and Johnson 1977). In Figure 13 we see the results. Weather and instrumental problems reduced the accuracy of our Hyades observations, but we can notice some interesting results: our bluest star is ρ Tau with $B - V = 0.24$, i.e., at a B - V where the field stars show the gap. Unfortunately we have only rather poor measurements for that star so our conclusions are somewhat shaky but it seems this star shows effects of convective energy transport.

For 57 Tau we have plotted both Oke's and our fall and spring measurements in order to give an impression of the uncertainties in the observation which Conti and Oke estimate for their measurements to be of the order of $0^m.02$. For the Hyades our uncertainties may be larger. We think that also for 57 Tau the convective energy distribution fits better than the radiative one, though it is not quite conclusive.

For the field stars our scanner results are seen on the left hand side of Figure 13. For stars with $B - V \geq 0.3$, all these stars clearly show the decrease in the UV as given by scaled Bilderberg models in indicating very efficient convective energy

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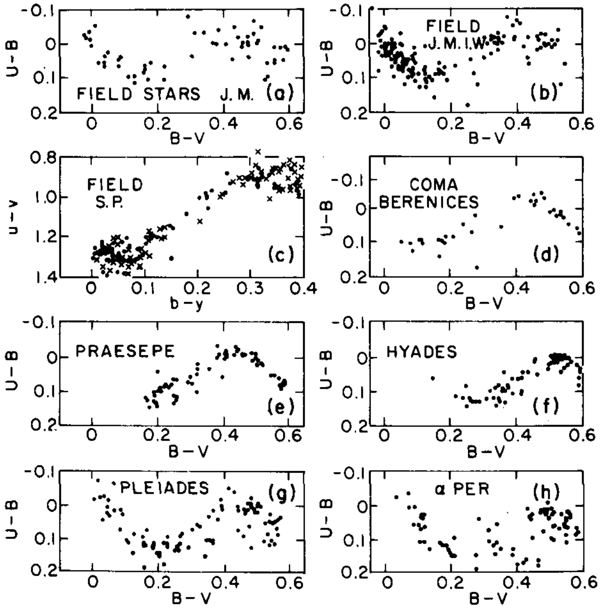

FIGURE 10:

The two color diagrams for field stars and different star clusters. This figure is taken from Böhm-Vitense and Canterna (1975) and is based on measurements by (a): Johnson and Morgan 1953; (b): Johnson et al. 1966; (c): Strömgren and Perry 1965; (d): Johnson and Knuckles 1955; (e): Johnson 1952; (f): Johnson et al. 1962; (g): Johnson and Mitchell 1958; (h): Mitchell 1960.

The gap for $0.22 < B - V < 0.29$ is very pronounced for field stars. It is present in most of the clusters, though not visible for the Pleiades.

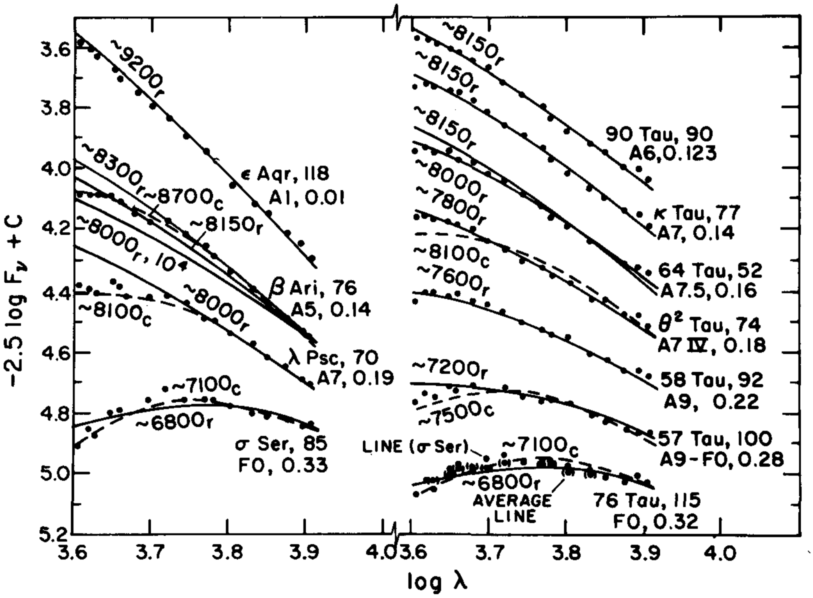

FIGURE 11:

Shows scanner observations (····) by Oke (1964) and by Baschek and Oke (1965) corrected for line blanketing and corrected for the new calibration by Oke and Schild (1970) and Hayes and Latham (1975). The points (·) and · demonstrate the difference obtained for the continuum with different measured line blanketing corrections. Also shown are the computed continuum energy distributions for radiative equilibrium models (————) and for scaled Bilderberg models (----). For the Hyades stars, shown in the right hand column, radiative equilibrium models can represent the observed distribution rather well if $B - V \leq 0.22$. For larger values of $B - V$ a reduction of the flux for $\lambda \sim 4000$ Å is apparent indicating a flat temperature gradient in the layers $\tau \gtrsim 1$. For the field stars shown on the left hand side the violet flux is reduced already for βAri with $B - V = 0.14$ and λ Psc with $B - V = 0.19$. The energy distributions can be represented quite well with scaled Bilderberg models, i.e. models with an unexpectedly large convective energy transport in layers with $\bar{\tau} \gtrsim 1$.

The number given beside the star name gives the rotational velocity vsin i, the number beside the spectral type gives B - V.

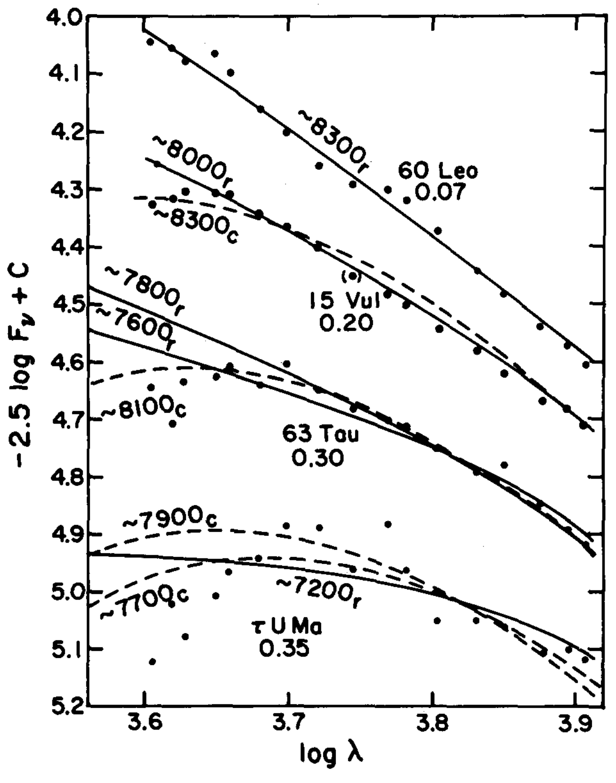

FIGURE 12:

Shows the A_m star scanner observations by Baschek and Oke (1965), corrected for line blanketing and the new calibration, (notation as in Figure 11). The bluest star, 60 Leo, can in the average be well represented by a radiative equilibrium model. (A discontinuity might be suggested at a wavelength, where a discontinuity in the OI continuous κ occurs). In 15 Vul with B - V = o.20 some convective energy transport may be present. For 63 Tau and τ UMa the flux reduction in the violet is even stronger than predicted by the scaled Bilderberg model, however, the line corrections may be somewhat uncertain.

For A_m stars convection appears to become important for about the same B - V as for normal stars.

transport in the top layers of the convection zone. For the field stars in the gap ($0.22 < B - V < 0.29$) we can almost match the observed energy distribution with radiative equilibrium models except for the sharp downturn just longward of the Balmer-jump. It seems they try to have convection like Hyades stars but do not quite make it. I do not understand this difference between the Hyades and the field stars.

In the last Figure 14 we have plotted the T_e , derived for the different stars by these comparisons of scans and computed energy distributions as a function of their B - V given in the literature. Also given are the spectral types and the $v_r \sin i$. The filled symbols indicate stars matching convective models, the open ones radiative equilibrium energy distributions. Stars for which the decision could not be clearly made are given in brackets. They are mostly the field stars in the gap. If we leave out these uncertain ones, then we see two sequences, one for radiative and one for convective energy distributions. The stars with high $v_r \sin i$ occur exclusively on the convective branch. I would interpret Figure 14 as telling us that generally convection will become efficient for $B - V \geq 0.22$, however fast rotation will cause an earlier onset of efficient convection leading to a reddening of the star by $\Delta(B - V) \simeq 0.07$ as given by the scaled Bilderberg models.

Could the decrease of the flux longward of 3647 Å be a direct result of rapid rotation without involving convection? Collins's results (1965) show that such an effect can only be expected if the star rotates close to the Roche Limit and if at the same time we look almost equator on, i.e., $\sin i \sim 1$. For A stars this should lead to $v_r \sin i \sim 350$ km/sec, which is much larger than the observed values.

Also indicated in Figure 14 are the values for the A_m stars. After correcting B - V for the additional line blanketing - Baschek determined $\Delta(B - V) \sim 0.05$-0.07 - they fall on the same two sequences defined by the normal stars. There does not seem to be any difference with respect to convection. I might mention that we cannot reproduce Baschek's and Oke's scanner measurements for any of the A_m stars which we measured, namely 15 Vul, τ UMa, 60 Leo, even though we do reproduce the energy distributions of normal stars, except for some minor discrepancies for 45 Tau. We are inclined to conclude that the A_m stars are all variable on time scales of the order of decades, a timescale that reminds one of the solar cycle. We are presently checking on the variability. This result is only preliminary.

III. SUMMARY

We have pointed out that stellar evolution computations presently need a good convection theory rather than give us relevant information. The measured micro-and macro-turbulent velocities may tell us something about convection, but we do not really know when. Temperature inhomogeneities are hard to measure. The continuum energy distribution in the UV for stars with $B - V \gtrsim 0.30$ clearly shows the effect of a reduced temperature

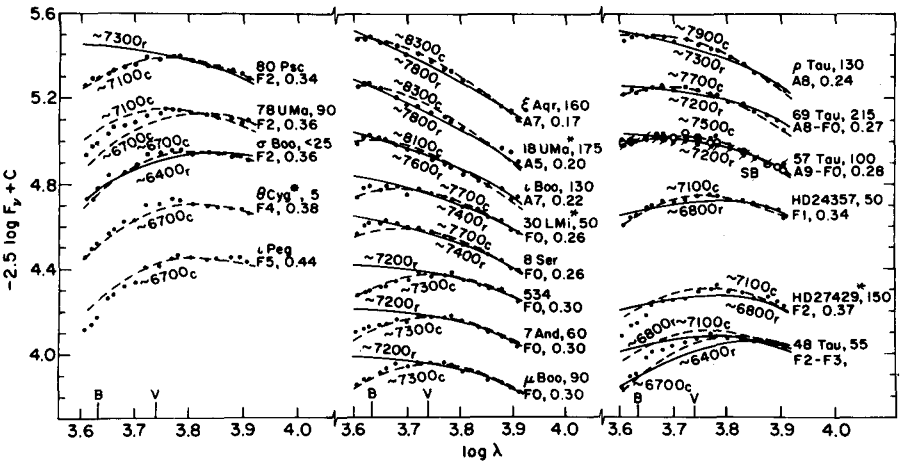

FIGURE 13:

Shows the scanner observations by Böhm-Vitense and P. Johnson (1977). For 57 Tau we compare 2 sets of measurements of Böhm-Vitense and Johnson with those of Baschek and Oke to give an impression of the uncertainties. *Indicates stars for which we have only 1 or 2 usable scans. Otherwise notation as in Figure 11.

The scans confirm our previous conclusions. The stars in the "gap" i.e. with $0.22 \lesssim B - V \lesssim 0.29$ show evidence of convection, the field stars as well as the Hyades stars. HD 27429, a rapidly rotating star, shows an especially large reduction of the blue and violet flux.

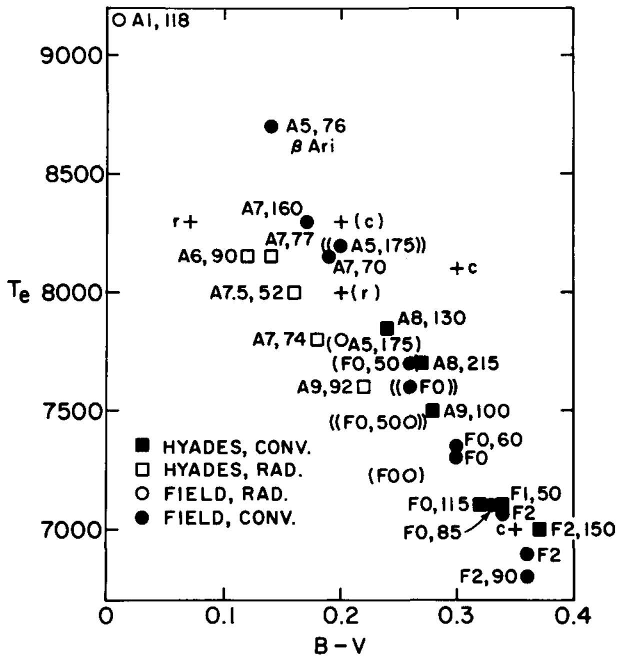

FIGURE 14:

Gives the relation between T_e and B - V as determined from the comparison of computed and observed energy distributions. Filled symbols indicate matches with scaled Bilderberg models, i.e. convective models, open symbols matches with radiative equilibrium models. Dubious cases are given in brackets, they always appear twice, once matched with a convective model and once with a purely radiative model. The spectral types and the rotational velocities $v_r \sin i$ are given for each star. Leaving out the dubious cases we find that for B - V $\gtrsim$ 0.30 all stars are convective. For smaller B - V we find two branches: One for radiative equilibrium stars and one for convective ones. The high $v_r \sin i$ occur all at the convective branch, indicating that rapid rotation appears to enforce convective energy transport in the late A stars rather than to inhibit it as was previously suggested (Böhm-Vitense and Canterna 1975).

This conclusion rests on the interpretation of the somewhat uncertain energy distributions of ρ Tau, 69 Tau and 57 Tau.

+r refers to radiative equilibirium A_m stars, +c to convective A_m stars. After correcting B - V for the additional line blanketing they fall on the same two branches as the non A_m stars.

gradient in layers $\bar{\tau} \gtrsim 2/3$ indicating an unexpectedly large convective energy flux in these layers. Stars with $B - V < 0.2$ and $v_r \sin i < 100$ km/sec mostly appear to be in radiative equilibrium. Stars with $0.10 < B - V < 0.30$ may be convective, they are always convective if they have large $v_r \sin i$.

The point $B - V = 0.30$ also marks the extension of the red boundary line of the instability strip to the main sequence. We take this as an additional evidence that this boundary line actually marks the onset of convection in the HR diagram. With local mixing length theory $\ell/H \simeq 1$ leads to agreement between the theoretical and observed boundary lines for convection, neither larger nor smaller values for ℓ/H will do.

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